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Patents Act 1990

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PROVISIONAL SPECIFICATION

Invention Title:

Diamond Single Photon Source

The invention is described in the following statement:

Title

Diamond Single Photon Source

Technical Field

This invention concerns a single photon source, and in particular such a source realised using diamond synthesis technology and optical waveguide technology. In another aspect the invention concerns a method for making such a source. In a further aspect the invention concerns a method for operating the source. The concepts involved bring together two fields: photonics and advanced materials processing.

Background Art

One of the most critical challenges facing experimentalists in quantum optics today, and relevant to the emerging field of quantum information processing, is the controlled generation of non-classical light, particularly single-photon quantum states. Presently, the ultimate implementation of linear optics quantum computing and quantum cryptography is underpinned by the development of a single photon source, which produces single photons on demand.

Some of the techniques being pursued for single photon sources are semiconductor quantum dots, fluorescing single molecules, attenuated lasers and nitrogen-vacancy colour centres in diamond. Fluorescing single molecules are limited in that they rapidly degrade with continuous excitation. Quantum dots have the advantage of a narrow linewidth, however require cryogenic temperatures for stable operation. The ideal single photon source would be stable at room temperature, display true single photon delivery and be free from photodegradation. The colour centre in diamond is the most promising, and combines the simplicity of single molecules with the robustness and stability of single atoms.

A nitrogen atom embedded in a diamond crystal and adjacent to an atom sized gap is known as a nitrogen vacancy (N-V) colour centre. The N-V centre in diamond has already been demonstrated to be an efficient source for single photons.[1] Antibunching experiments[2] have been performed which demonstrate true single photon delivery and

[1] C. Kurtsiefer, S. Mayer, P. Sarda, H. Weinfurter, Phys. Rev. Lett. 85, 290 (2000).
[2] R. Brouri, A. Beveratos, J.-Ph. Poizat, Ph. Grangier, Opt. Lett. 25, 1294 (2000).

quantum encryption has been demonstrated in free space using N-V diamond single photons.[3]

However, light from a single isolated N-V centre is emitted isotropically, thus making efficient light collection problematic for single photon applications. The current favoured technique for light collection employs an objective lens focused on the N-V centre and is limited by the numerical aperture of the lens. This technique is cumbersome and inefficient.

Disclosure of the Invention

The invention is a single photon source, comprising a nitrogen-vacancy colour centre in synthetic diamond which in turn is embedded in the core of an optical waveguide.

Embedding the single photon source in a waveguide overcomes the use of light collection optics, as the photons are readily coupled into the waveguide due to their location on the fibre core. Optical fibre or planar waveguides may be employed with this technology.

Such a waveguide embedded diamond single photon source is suitable for quantum information processing technologies, such as quantum key distribution (QKD). It also has potential application in linear optics quantum computing.

The performance of diamond single photon sources may be optimised to far exceed other potential systems with respect to ease of production, room temperature stability, durability and lifetime (which is virtually unlimited).

Another aspect of the invention is a method for making a single photon source, using, for instance, an optical fibre waveguide, comprising the steps of:

Cleaving or polishing an optical fibre end face;

Diamond seeding the end face, for instance immersing the fibre in an ultrasonic bath of methanol and diamond suspension.

Growing diamond on the end face, on the core, for instance using a microwave chemical vapour deposition reactor.

Producing an NV centre in the diamond nanocrystal, for instance by controlling the level of nitrogen doping during the diamond growth process.

[3] A. Beveratos, R. Brouri, T. Gaçoin, A. Villing, J.-P. Poizat, P. Grangier, Phys. Rev. Lett. 89, 187901-1 (2002).

Optionally embedding the diamond nanocrystal in a continuous length of optical fibre, for instance by fusing the end face having the diamond nanocrystal with a bare optical fibre end face to form a virtually seamless strand of optical fibre with the diamond nanocrystal embedded in the fibre core.

By situating the NV containing diamond nanocrystallites in the core of an optical fibre, the luminescence output is coupled to the fibre core. Such a 'doped' fibre is immediately usable as a single photon source emitting single photons centred around 637 nm in response to laser pulses at, for instance, 514 nm.

A laser source may then be coupled to a first end of the strand of optical fibre in order to impinge only on the nanocrystal located on the fibre core The laser may also be made to impinge on the diamond from the side of the optical fibre thus perpendicularly through the cladding.

Single photons may be coherently generated by embedding the single photon source in an optical cavity and, using standard optical techniques, such as stimulated Raman adiabatic passage, to coherently generate a single photon in the cavity mode. Further, flying qubits can be coherently generated from the stationary qubits where the N-V centre of the diamond constitutes the stationary qubit and the photon, generated coherently by the above process, constitutes the flying qubit.

In a further aspect the invention is a method for operating the single photon source, comprising the step of:

injecting laser pulses into a first end of the strand of optical fibre to excite the device to emit a single photon which, depending on the direction of the emitted photon, travels to one end of the strand of optical fibre.

A wavelength dependent attenuation filter or grating may be located on the output end of the strand of optical fibre to filter the pump frequency.

Brief Description of the Drawings

An example of the invention will now be described with reference to the accompanying drawings, in which:

Fig. 1 is a schematic diagram of a single photon source.

Fig. 2 is a magnified image of diamond crystallites deposited by plasma enhanced chemical vapour deposition on cleaved and seeded end faces of optical fibres.

Fig. 3 is a higher magnification image which shows individual crystallites, some of which are located directly on the fibre core (marked by an arrow).

The images of Fig. 2 and 3 have been obtained using a scanning electron microscope.

Best Modes of the Invention

The single photon source

Referring first to Fig. 1, the single photon source 10, comprises a nitrogen-vacancy colour centre 12 in a synthetic diamond nanocrystal 14 which in turn is embedded in the core 15 of an optical waveguide 16. A laser source 18 at one end of the waveguide emits laser pulses 20 which cause the source to emit single photons 22 which are coupled to the optical fibre and emitted from the one or the other end 24. The laser pulse continues to propagate along the fibre.

The following steps are involved in the fabrication of the diamond single photon source using, for instance, an optical fibre:

Sample preparation

Optical fibres are prepared by stripping the protective jacket and "cleaving" each fibre end face to create a flat surface. Bundles of cleaved fibres are assembled and secured in a tantalum tube and diamond seeded using an ultrasonic bath of methanol and diamond suspension. The fibres are then mounted in a sample holder for diamond growth in the CVD reactor.

Diamond growth

A 1.5 kW microwave chemical vapour deposition reactor is employed to grow diamond nanocrystals on optical fibre end faces. The process includes the use of hydrogen and carbon containing gases with small amounts of nitrogen. The nitrogen-doping levels are carefully controlled during the diamond growing process to allow for isolated N-V centres to form within the diamond lattice.

Fig. 2 shows adjacent individual fibres within a prepared fibre bundle with diamond crystallites on the fibre end faces, and Fig. 3 is a high-magnification view of crystallites deposited on the core region.

Assembly

Once a diamond containing an NV centre is grown on the core of the fibre end face, the diamond is embedded in a continuous length of optical fibre. This is done using existing fibre splicing technology; as used extensively in the telecommunications industry. The diamond coated fibres are fused with bare fibres to form a strand of optical fibre with a diamond nanocrystal embedded in the fibre core. The end product will ideally be a robust, readily implemented single photon source.

Device operation

The final device will operate using a pulsed laser source, for instance pulses from a 514 or 532 nm laser source which is coupled into a first end of the fibre. The pulses are injected into the first end of the strand of optical fibre and each pulse that arrives at the device excites a spectral transition in the N-V centre and causes the device to emit a single photon in a wavelength band centred around 638 nm. Some of the generated photons will be coupled with very high efficiency into the fibre waveguide due to the N-V centre's location within the fibre core. At the output end of the fibre, the pump frequency is filtered with a wavelength dependent attenuation filter or a grating.

Characterisation

Diamond deposits can be analysed using a micro-Raman spectrometer to give a measure of the crystalline quality of the material (sp^3/sp^2 carbon content). Photoluminescence spectroscopy, performed on the same machine, will reveal the luminescence from the N-V colour centre. This will give an approximate measure of the concentration of N-V centres in the lattice. The nitrogen doping can then be adjusted to give isolated N-V centres. The spectrometer can be operated in scanning-mode, which allows for a 2D scan of the sample. Using this technique, the isolated N-V centres can be pin pointed.

Single photon detection

Verification of single photon generation is accomplished by demonstrating a quantum mechanical property called photon antibunching. That is, during the excitation and emission period of a single N-V centre, one and only one photon is emitted. Two high-sensitivity, low noise avalanche photo-diodes and a correlator are used to perform the antibunching experiments. To demonstrate antibunching, the N-V centre is excited using a continuous wave (CW) laser. Because the excitation, relaxation and emission process takes approximately 11.7 ns, single photons will have a mean temporal separation of 11.7 ns.

Industrial Application

Applications for single photon sources lie primarily in the area of quantum information processing (QIP). For example, quantum key distribution (QKD) which uses single photon sources for secure information exchange. QKD is only one branch of QIP which also includes optical quantum computing and information storage.

It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

Dated this second day of March 2004

Qucor Pty Ltd
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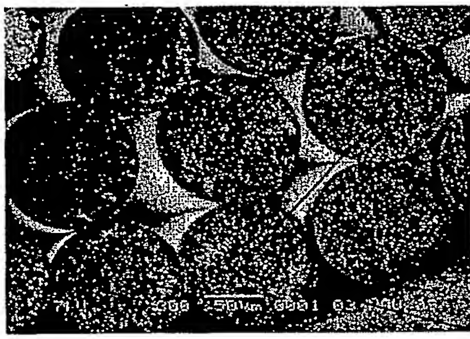

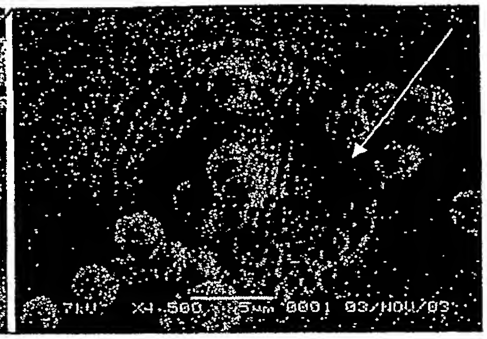

Fig. 2

Fig. 3

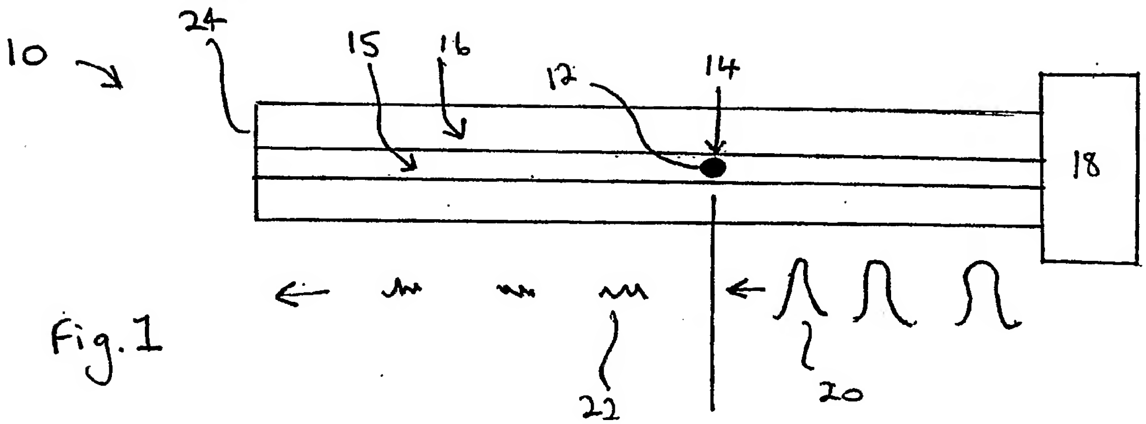

Fig. 1